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Modeling individual's light switching behavior to understand lighting energy use of office building

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Abstract

It is usually observed in office buildings that despite the randomness and diversity of occupants' light switching behavior, the lighting usage profile for each space level (e.g. room, floor, and building) looks more regular and deterministic as the space scale and the number of occupants increases. To explain the phenomena, this study proposed an agent based modeling and simulation approach to analyze the impact of occupant behaviors on the lighting energy usage in office buildings. A type of crowd effect can be found by simulation, which reveals the different characteristics of lighting energy consumption among different sized offices.

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Keywords: Lighting usage; office building; occupant behavior; conditional probability model; crowd effect

1. Introduction

Lighting accounts for 20–40% of total energy consumption in office buildings [1]. The study of lighting energy consumption of office building is crucial for energy saving. An interesting finding from in-situ studies is that the energy consumption of small and large-scaled commercial buildings differs remarkably. Large scaled buildings consume 3-8 times more energy than small-scaled buildings per unit area [2]. Zhou et al [3] analyzed the main characteristics of measured lighting energy use data of 15 large office buildings (manual lighting control) in Beijing and Hong Kong and found that in these office buildings, the 24-hourly variation in lighting energy use was mainly driven by the presence schedules of the building occupants rather than the outdoor illuminance levels; the lighting energy usage profiles between single offices and large offices, from room to zone, from floor to building, and for different sized

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buildings are significantly different. Yun et al [4, 5] also found that the lighting use patterns in large offices did not have a statistically significant relationship with illuminance levels and that in small office is just the opposite.

The above phenomena are closely related to occupant behaviors on lighting use but have not yet answered by the existing building energy modeling tools. Commonly in building simulation programs, fixed schedules for typical days are assumed to represent the dynamics of lighting energy use in buildings. This approach does not address the stochastic nature of occupant light switching behaviors and the relationship between those behaviors with indoor illuminance. To overcome it, some advanced lighting behavior models have been proposed [6-9], which relate the use of artificial lighting to daylight levels and occupancy and suggested the probability of switching on light as a regression function of illuminance levels. Based on the field studies, numerous researchers [10-17] proposed the calculation method to predict the lighting energy demand, evaluate the performance of manually and automatically controlled electric lighting systems, or estimate energy savings of artificial lighting use from daylighting. These studies have made great progress to help understand and quantify occupants' light switching behavior in office building. However, the existing models are empirically regressed according to a large amount of people and not fit to describe occupants' individual diversity, and there are no specific explanation for the usually observed phenomena in office buildings that despite the randomness and diversity of occupants' light switching behavior, 1) the lighting energy usage profile for each space level (e.g. room, zone, floor, building) looks more regular and deterministic as the space scale increases; 2) the lighting energy usage profile of multi-person office looks more regular than that of single office.

This paper proposes an agent based modeling and simulation approach for occupant behavior and is aimed to quantify and explain the difference in lighting-related energy consumption in different sized offices. It is based on previous work in the building occupancy simulation [18, 19]. With this approach, we first model the individuals' lighting switching behaviors and secondly extend the models to the multiple-occupant situation. Finally, we use agent based simulation to explain how the difference of the lighting energy consumption between private and large open-plan offices come from, and also between the small and large-scaled office buildings.

2. Individual's Light Switching Behavior Models

Based on a questionnaire result and measurement data of private offices, we can use the conditional probability model to describe the lighting usage of the occupants. The conditional probability model developed by our group has been proved feasible in air-conditioner usage in residential buildings [20, 21]. To use the model, occupant action patterns shall be informed first, for the pre-selection of the function form. Then the 10-minute step measurement data is used to do the statistics and function fitting to get the parameters of the model. In this way the lighting usage model of a single agent in a private office can be developed.

From the questionnaire results of the measured private offices, we can get the driving forces behind turning lights on and off. The lighting usage pattern options follow two principal lines: (i) influenced by personnel movement or other events (by choosing the option of "turn on the light once entering the office" and "turn off the light once leaving the office") and (ii) work plane illumination (by choosing the option of "turn on the light when feeling dark" and "turn off the light when feeling bright enough").

The patterns work in a random way:

1) When the occupant enters the office, he or she has a chance to judge whether to turn on the light according to the indoor illuminance then (if the light is off);

2) When he or she stays in the office, a probability comes up every time step to judge whether to turn on the light according to the daylight illuminance (if the light is off);
3) When the occupant stays in the office and the light is on, a probability comes up every time step to judge whether to turn off the light according to the indoor illuminance;
4) When the occupant leaves the office, he or she has a chance to judge whether to turn off the light according to how long he or she leaves (if the light is on).

In the conditional probability model frame, a certain mathematical function can be corresponded to every lighting usage pattern, which is shown in Table 1.

Table 1 Description of individual's light switching behavior

No.	Pattern description	Mathematical model
1	Turn on the light when feeling dark	$P=\begin{cases}1-e^{-\left(\frac{u-x}{l}\right)^{k}\frac{\Delta\tau}{\tau_c}}, x\le u\\ 0, x>u\end{cases}$, *when occupied*
2	Turn on the light once entering the office	$P=\begin{cases}1-e^{-c\left(\frac{u-x}{l}\right)^{k}}, x\le u\\ 0, x>u\end{cases}$
3	Turn off the light when feeling bright enough	$P=\begin{cases}1-e^{-\left(\frac{x-u}{l}\right)^{k}\frac{\Delta\tau}{\tau_c}}, x\ge u\\ 0, x<u\end{cases}$, *when occupied*
4	Turn off the light once leaving the office	$P=1-e^{-\left(\frac{t_{leave}}{\tau_c}\right)^{k}}$

x: work plane illumination;
u, l, k, c: parameters of the function;
$\Delta\tau$: time step;
τ_c: time constant, equals 1 hour;
t_{leave}: time lasted during the occupant away from the office.

3. Agent-based Simulation

To describe the lighting usage in multi-person situation, e.g. in a large open-plan office, several assumptions for occupants' interactions have to be proposed before the above individual model is used in a multi-person situation.

1) Every occupant in a large open-plan office has his own basic lighting usage behavior as the same as when he is in a private office.
2) Lighting usage behavior is interacted among the occupants based on his own basic behavior, for example when there are other people in the office, the turning-off light action won't happen; while the turning-on light action is not influenced by others.
3) The lighting system is controlled by every occupant in the office with equal right.

Based on these hypotheses, we can perform agent-based simulation for the scenario of any number of occupant's uses of lights in office buildings.

4. Simulation of Crowd Effect

A large open-plan office is used to illustrate the process and results of the agent-based modeling and simulation of occupant lighting behavior. The simulation of occupant movement process (enter in or leave out) is performed before lighting behavior simulation

In this simulation case, as the number of occupants rises from 1 to 5 and then to 20, we can see some interesting result showing the different features of lighting usage when occupants number increases.

The simulation results for a typical day are shown in Figure 1, from which we can preliminarily see that as the number of occupants rises, lighting operation time increases. Indeed, when there are 20 occupants in the office, the lights are on nearly throughout the working time. For accurate comparison purposes, a 126-day simulation based on the real measurement is done and the results are shown in Figure 2, which presents the average daily lighting operation time for different numbers of occupants. We see that quantitatively lighting operation time is longer as there are more occupants in the office.

When the simulation is repeated a number of times, the variability among the results every time can reflect the randomness in the real process to some extent. As shown in Table 2 and Figure 3, the 126-day simulation is repeated for 100 times. The simulation daily lighting operation time, the standard deviation among different simulation times and the coefficient of variability are conducted with different occupant number in the office. Coefficient of variability (CV=standard deviation (SD)/mean) is an important value for describing the stability. When we use the CV index, the influence of different data sizes is removed, and this allows us to describe the randomness of different conditions precisely. The smaller the CV is, the more concentrated are the data and the lower is the degree of randomness; from the viewpoint of physics, this means that the lighting schedule is more regular and thus energy consumption is more concentrated and stable. Concluded from the table, when occupant number increases, the CV lighting operation time increases, and the lighting schedule is more regular with less randomness.

Table 2 The influence of the crowd effect based on a different number of occupants

Numbers of occupants	**W=1**	**W=5**	**W=20**
Simulation daily lighting operation time (h/day)	0.50	1.07	1.48
Standard deviation among different simulation times (h)	0.1352	0.1668	0.1639
Coefficient of variability	0.2718	0.1561	0.1109

The phenomena found above can be described as a type of crowd effect. This effect is usually found in multi-person situation as large open-plan offices. When occupants gather to a certain degree, lighting-related energy consumption is affected. The interactions among multiple occupants lead to a longer lighting operation time and thus higher energy consumption. Further, as the number of occupants in a room increases, even if occupant behavior varies from person to person, the randomness of lighting use weakens, the lighting schedule becomes more regular, and lighting operation time reaches a steady level. The crowd effect explains the different features of lighting usage between private and large open-plan offices appropriately.

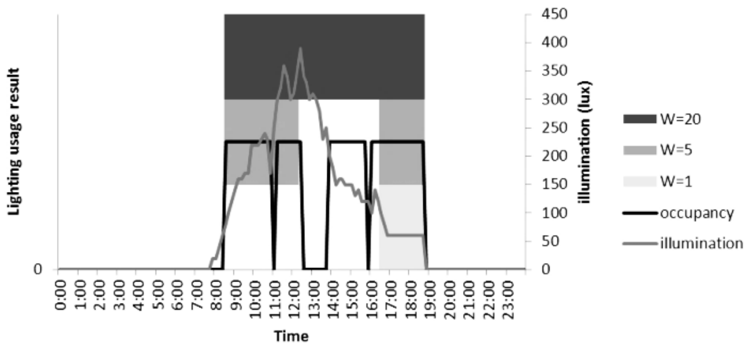

Figure 1 The simulation results of lighting operation time with a different number of occupants for a typical day (W is the number of occupants in the room)

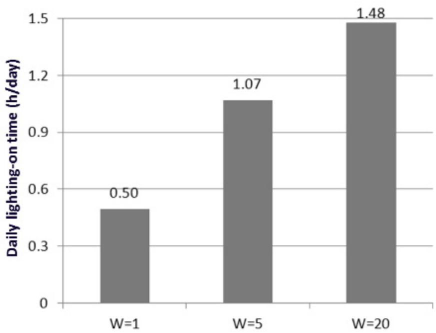

Figure 2 The simulation results of lighting operation time with a different number of occupants for a long-term period (W is the number of occupants in the room)

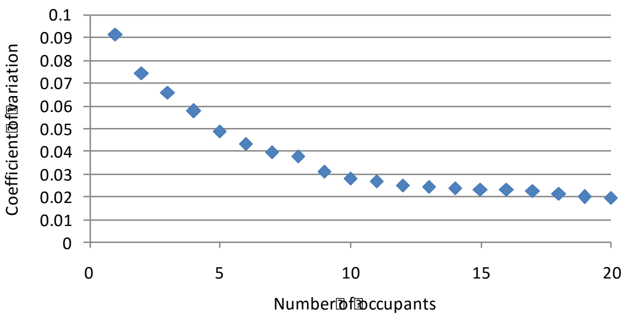

Figure 3 Coefficient of variation over number of occupants

5. Conclusions

This study presents an agent-based modeling and simulation approach to describe occupants' light switching behavior and their impact on lighting energy consumption in office buildings. The lighting usage model presented herein reflects the environment- and event-related driving forces behind lighting usage in office buildings and describes the degree to which these factors influence lighting use. A three-parameter function and probability relations are also used to describe the random process of lighting use.

The application of occupants' light switching behavior can calculate the lighting energy use of offices with different occupants and different lighting behaviors. Based on the simulation, we find the phenomena called the crowd effect, namely that an increase in the number of occupants in an office results in a more regular schedule, a longer lighting operation time, and less influence by different behaviors. Also the increase in the number of occupants make the individual behavior pattern not as notable as in a private office. It shows that agent based modeling and simulation of occupant behavior can help to understand the real energy usage in office buildings.

In terms of future research, more work is still needed in studying the occupant behavior model in buildings. Using the occupant behavior model to build simulations would be a promising area for the improvement of the building simulation study.

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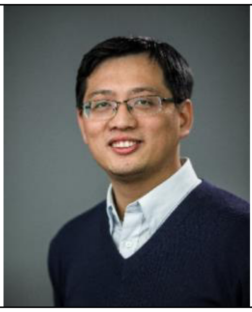

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